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AN EVALUATION OF AN ALTERNATIVE SUPPLY SYSTEM TO SUPPORT THE REPUBLIC OF CHINA'S ARMY

by

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March, 1996

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The results were that without considerations of cost savings that may be realized in such a system the POS system produced a small increase in the readiness of the battalion. Chapter V presents the author's conclusions and recommendations for a more detailed and rigorous study of the proposed alternative supply system.

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AN EVALUATION OF AN ALTERNATIVE SUPPLY SYSTEM TO SUPPORT THE REPUBLIC OF CHINA'S ARMY

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ABSTRACT

This study examines the effect of a Point of Sales (POS) type of military supply system on the readiness of a typical Republic of China infantry battalion. The study compares the current system against the POS-like system. Chapter II is a background of the current supply system and the alternative system studied in the thesis. Chapter III develops a stochastic model to generate parts availability probability values for the support of three types of equipment assigned to a battalion. Chapter IV uses these probabilities to populate a decision tree for the determination of which system will increase the readiness of the battalion. A GAMS Program is used in Chapter III to generate the probabilities for support and a Decision Support Program (Data) is used to develop the decision tree and for the analysis of the results.

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EXECUTIVE SUMMARY

The Republic of China's (ROC's) defense forces are primarily engaged in a defensive role within the immediate geographic area of the ROC. As is the case with most nations since the end of the cold war, the ROC is reducing its defense expenditures and examining its defense structure for the purpose of making it more capable and more efficient. The supply system which supports the ROC Armed Forces is designed and based on the U.S. Armed Forces' supply model. The U.S. Armed Forces model is intended to support a force that has global commitments and may be deployed far forward of a friendly supply source.

This thesis studies the effect of an alternative supply system on the availability of three types of equipment assigned to a typical ROC Army infantry battalion. The current supply system in a much reduced form is compared against a Point of Sale (POS) type of supply system to determine its effects on the readiness of the infantry battalion.

Point of Sale systems are used in the civilian world to support small retail outlets from a central location. These systems are characterized by rapid communication systems, computer technology and the use of package delivery services that have appeared commercially over the last decade. The major effect of these systems is a very rapid response to trends and customer needs. For example, a small clothing store sells an item which has recently become popular. Current sales information is combined with information from many other small outlets in the corporation's information system. A computer analysis detects the trend change and orders the corporation's warehouses to make up shipments for this item to the company's outlets based on the inventory levels at each of the stores. This centralized operation reduces the company's cost of doing business and at the same time, decrease its response time. In the ultimate examples of Point of Sale systems, the sales clerk's scan with a bar code scanner is entered directly into the computer. That computer transfers that single piece of information to the corporate computer, an analysis program in the corporate computer detects the trend and consults the inventory database, and finally, an automated warehouse makes up the shipment packages for the package delivery service. In this system, human error is reduced dramatically with the use of current computer technologies.

Two characteristics most important in a military context are the reduction of errors and the rapid response time of a Point of Sale system. The ROC's Armed Forces are supplied from the Island

of Taiwan which is also where the vast majority of those forces are deployed. This situation means that the ROC Armed Forces could replace their existing supply system with one based on a Point of Sale model.

The study reported in this thesis does not address the economic differences between the current supply system and the alternative Point-of-Sale-like system. The thesis simply addresses whether a single Army battalion's readiness would increase with a supply system that responds faster and more accurately to the battalion's needs.

The study first develops an optimized model of the current supply system. Parts availability probabilities are sought which maximize equipment uptime, and the model produces the probabilities (for the three types of equipment) of a needed part for their repair being available on one of the four levels of the ROC supply system. These probabilities would reflect the situation when the current supply system is performing at its very best.

Next, these probabilities are used to populate a decision tree which represents both the current supply system and the alternative system. An analysis is performed on the results of the decision tree, with operational readiness as the measure of effectiveness.

The model's results indicate that there would be an improvement in the readiness of the Army battalion with a Point of Sale system. If these results were coupled with a cost analysis for the two supply systems which favored the POS system, the combination of a cost savings and an increase in readiness would, in the author's opinion, lead the ROC to select a Point of Sale system.

I. INTRODUCTION

At the end of World War II, the Republic of China (ROC) Army logistic structure was similar to the United States Armed Forces supply system. At the time, these supply systems were probably among the most efficient and effective systems employed in the world. Since that time, civilian systems have benefited from new management techniques and technology and have replaced military systems at the leading edge of efficient supply systems. Additionally, the U.S. supply system is designed for a nation with world-wide military commitments and responsibilities. The U. S. system also supports a very large force that is deployed over large distances. The ROC's Forces are committed to the defense of the ROC and the area near the Island of Taiwan.

Although the ROC's has developed business interests in mainland China, the mainland still holds military maneuvers from time to time which threaten the Island. Mainland China has never given up the idea that they may use military force to resolve the Taiwan issue. The ROC's Armed Forces are mainly defensive and, unless history-making changes take place, will be employed in the defense of Taiwan into the indefinite future. The defense budget of the ROC remains high and is a burden to the ROC's economy. In order to realize the most efficient use of resources for the defense of the Island of Taiwan, the ROC must use modern management techniques and be innovative and responsive to the special circumstances of the ROC. The purpose of this thesis is to propose and investigate a more efficient method of supplying military units on the Island of Taiwan.

A. REPUBLIC OF CHINA'S CURRENT SUPPLY SYSTEM

The current supply system used by the ROC may be viewed as a many-layered hierarchy, whose primary function is enabling the flow of information from the maintenance personnel at the lowest level to contractors and suppliers of material. This system represents at least fifty years of evolution and design.

This system was originally constructed in the era of the "paper office." Its internal structure represents the paper flow and record keeping of the 1940s through the 1960s, and

was designed to function without the use of computers. Generally, in the 1970s, these systems were computerized, but the basic structure of paper flow was maintained.

The supply system as it currently exists was designed to facilitate the movement of information using the information technology of the 1940s, forms and paperwork via the mail system. The system has evolved so that, at the current time, the forms are still filled out but rather than physically moving the forms to their destination, they are transmitted via telecommunications and stored and processed using some information processing techniques. Essentially the supply system that exists currently is a system which uses the most advanced technology to perform a 1940s style operation. This thesis proposes an alternative supply system that uses 1990s technology and is like the commercial Point of Sale system.

B. COMMERCIAL POINT OF SALE SYSTEM

A contrast to the above description is the civilian Point of Sale (POS) system used in the retail market. This system uses the latest computer and communication technologies to communicate directly from the lowest level to the centralized supply of the corporation. There are very few levels in the hierarchy, and emphasis is placed on efficient use of technology to serve customers. In the ultimate examples of this system, a retail clerk will scan a code as they sell an item of clothing. This information will be transferred directly to the corporate headquarters for the decision making process and the identification of trends in the clothing business. The information also will be used by the corporations warehousing operation to reorder the item sold in the store. The item in the store will be replaced via UPS or Federal Express. This may even be done robotically inside the warehouse, and the only human action taking place is when the store clerk sells the item.

C. OBJECTIVES OF THIS RESEARCH

The overall objective of this study is to examine a proposed replacement for the ROC Armed Forces' logistics system. This system would be based on the advanced retail systems used in the U.S. commercially, generally referred to as Point of Sale systems. For the purpose of the study, the discussion will be limited to the current logistics system of the ROC Army,

because it is well-known to the author and it is representative of logistics throughout the ROC Armed Forces.

In order to quantify whether the replacement system is better than the current system, a model will be developed that will represent the readiness of a battalion level Army unit as it relates to supply functions. In such a military application, this readiness could be considered equivalent to profit in a civilian retail application. A commercial organization would not consider using (or changing to) any system which would not produce a profit; analogously, no military organization would change to a system that does not maintain or increase a unit's readiness.

To model both systems, first a model of the current system will be developed that will represent the best possible operation of the current system. This model will generate the probabilities for repair parts being available for an Army battalion's equipment at each level of the current supply system. These probabilities will be used in Chapter IV to model both the current supply system and the alternative supply system. The reason the author has developed a best possible situation for the current supply system, is that no data exists for the alternative supply system. In order to compare the two systems, a model is developed that compares the best possible system against the alternative system using the same conditions.

D. LIMITATIONS OF THIS STUDY

This study is limited to the example of supply support for a battalion-level Army unit in the ROC. This study will not address matters of the reorganization that would result if the replacement supply system were actually implemented. Also, the study will not address the computer or network systems required to make a Point of Sale type of system successful in supporting the armed forces' logistics requirements. The study is limited to determining mathematically whether the system proposed in the study will increase the readiness of the battalion level unit and contribute to a more efficient supply system for the ROC.

E. ORGANIZATION OF THE STUDY

This chapter has given a brief background outlining the subject of the study and presenting its objectives. Chapter II presents the current ROC Army logistics system and its functions. This chapter will also present the characteristics of a commercial Point of Sale system. The final portion of Chapter II outlines the characteristics of a proposed alternate military supply system based on a Point of Sale system. Chapter III will introduce stochastic modeling and present the GAMS Program used the by the author to construct the supply model. This model and the data are based on the author's experience. Chapter III will present the non-linear programming model used to calculate parts availability probability values for the support of three types of equipment assigned to a battalion. Chapter IV will introduce a decision tree produced with the author's data and model created in Chapter III. A sensitivity analysis will be done on the results to identify the factors which have the most effect on the model. Chapter V presents the author's conclusions and recommendations.

II. LOGISTICS SUPPORT

There are three supply support systems relevant to this study. They are:

- The supply support system currently in use by the ROC Army,
- The Point of Sale (or POS) system employed by many retail companies, and
- A proposed adaptation of the POS system for use in the ROC Army.

Each of these three supply support systems will be described in this chapter. The first section is an overview of the ROCs Logistics Agency. The second section is a general background on Point of Sale systems used in retail operations. The third section will be a description of the alternate system for the ROCs current supply system based on the Point of Sale system in the second section. Finally, there will be a brief discussion of a Measure of Effectiveness (MOE) which will be used in the study to evaluate the current system and its alternate.

The purpose of this chapter is to give the reader a background on the supply systems of interest in this study. This is necessary in order that the reader has a common image of the two supply systems that will be compared in the study. Countries have varying methods of supporting their military forces and it must be emphasized that the "current" system described in this chapter is the ROC Army's logistic support system.

A. THE ARMY LOGISTICS AGENCY

Maintenance and supply are very important elements in a unit's readiness. The Army Logistics Agency provides these services to Army units and is a key element in the defense of the ROC. The organization of this agency is shown in Figure 1. Figure 1 shows the four service levels used to provide supply support to the ROC Army. Each service level is made up of a maintenance level and the inventory level that supports that maintenance level. Each level is identified with an upper case roman numeral. For example, ML I represents Maintenance Level I, the lowest maintenance level. This maintenance level is supported by Inventory Level I (IL I), the lowest inventory or supply level in the Army Logistics Agency.

1. The Function of the Logistics Agency

In the ROC Army, supply services and maintenance are closely associated. Most supply services are performed in support of maintenance units attached to various sizes of Army units. (The exceptions to this are the purchase of new equipment and the supply functions associated with munitions and magazines.) Additionally, supply must support the day-to-day use of material expended throughout the Army. Examples are uniforms, paper, etc. For the purpose of this study and the modeling of the supply systems, only the maintenance support will be considered. This type of support uses the largest percentage of the supply services resources and is a representative scenario for the problem to be solved.

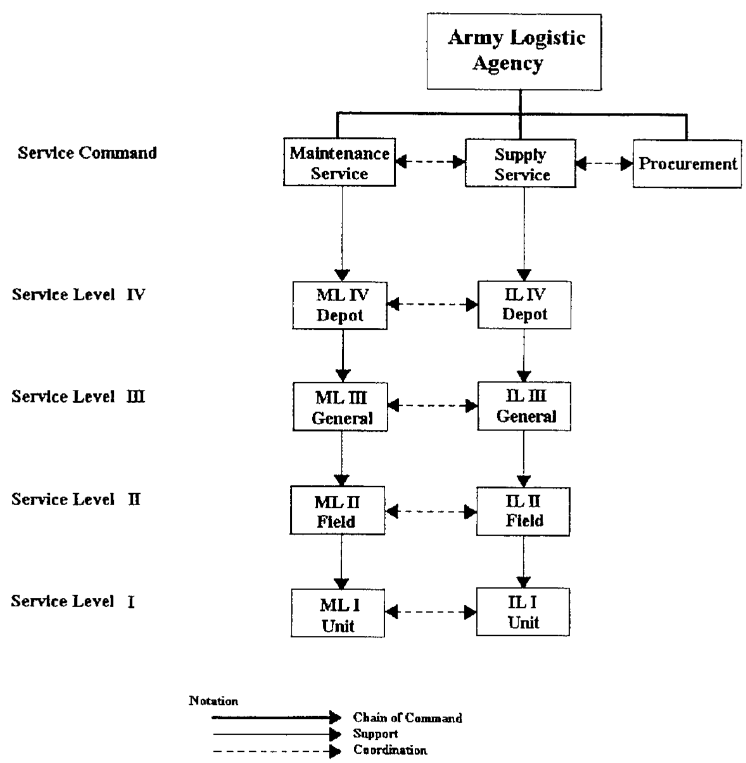

Figure 1. ROC Army Logistics Agency Organization

a. ***Maintenance Services***

Maintenance services are divided into four levels that roughly correspond to the size of the Army units that the maintenance units support. These maintenance levels are called MLI, MLII, MLIII, and MLIV.

Maintenance Level I (ML I) involves organizational maintenance in support of units of battalion size. This maintenance unit is a platoon which is responsible for preventative maintenance of equipment used by the battalion. Examples are lubrication, cleaning, and adjustment of vehicles. This may include the changing of the vehicles tires after an inspection is performed, and the decision making process for determining when the vehicle must be moved to a higher maintenance level.

Maintenance Level II (MLII) involves large organizational maintenance and supports units of divisional size. These maintenance units are called Support Battalions and serve four types of divisions: armored, mechanized infantry, heavy infantry and light infantry. The nature of support at this level depends upon the division being supported and is field support, intended to be in place in combat in the divisional rear area.

Maintenance Level III (ML III), intermediate maintenance level, supports the ROC Army in general and performs maintenance on major components of equipment which are not repairable at the organizational level. This is an industrial operation and is staffed by both military and civilian specialists expert in that type of maintenance. Examples are the repair of electronic equipment, changing engines, etc.

Maintenance Level IV (ML IV), depot maintenance, supports the ROC Army and performs overhaul and sophisticated maintenance of major pieces of equipment used by the Army. This is also an industrial operation staffed by both military and civilian specialists. Equipment repaired at this level is then considered new equipment, and is reissued to the Army.

b. ***Supply Services***

Supply services in general performs three functions: inventory control, procurement, and distribution. *Inventory control* is the process of insuring that the systems inventory level meets the readiness requirements of the particular maintenance level involved.

This function must keep track of literally tens of thousands of parts and their commercial source. Inventories for purposes of supply are kept at each of the four Maintenance Levels. Such an inventory is created with historical data and new procurement data and is designed specifically to support the maintenance unit at that level. *Procurement* is the process of procuring both new equipment and parts to maintain existing equipment. Procurement is responsible for the purchase of the most economic lot size of any particular item. *Distribution* is responsible for the delivery of the parts or equipment to the maintenance level that has requested that equipment, and to the inventory operation at that level when replacing stock.

2. Model of the Existing System

Figure 2 is a representation of the flow of supply requests and supply material in the ROC Army's existing supply system. In the figure the light arrows show directions of supply requests, while dark arrows show movement of supply material. Supply requests from the lowest level are made to the inventory operation at that level. If the request cannot be filled at that inventory level, a request is made to the next level in the chain until it can be filled. If it cannot be filled by the system, then the procurement division of the ROC Army's Logistics Agency will purchase it from commercial sources. This can amount to as many as ten separate transactions to satisfy a request from the lowest level units. Additionally, the management of the maintenance and inventory system is based upon requests for parts, rather than their actual use. This may lead to problems in inventory management, and poor positioning of parts to support some units.

B. POINT OF SALE SYSTEMS

Point of Sale (POS) systems have evolved considerably since their introduction in the early 1980s. Initially, they were designed to monitor cash balances of retail outlets, but current systems have become very sophisticated, providing measures of many different aspects of the retail operation. Because these systems evolved in the era of small computers and telecommunications, they are designed around those technologies. Because the lowest node in the system is a PC with its open architecture, these systems can be expected to remain up-to-date. The flexibility of the PC and its communication system allow management to

tailor the retail outlet with software for both management's information needs and any special needs of the retail operation. [Ref. 6]

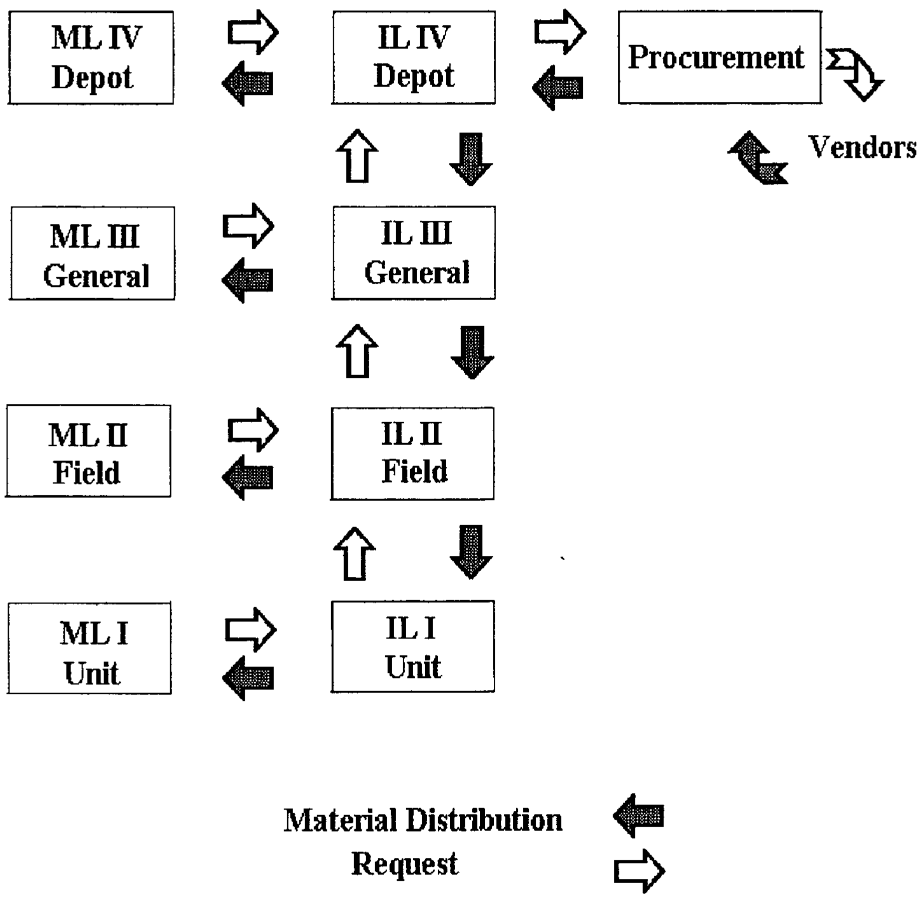

Figure 2. Current Supply System Flow of Information and Material

A key feature of Point of Sale systems is their almost instant response to the changing needs of the company's customers. For example, in a clothing outlet, the corporation can track the changing fashion trends on a daily basis and adjust the shipments to their outlets to reflect those trends. Additionally, historical information will allow the company to estimate the quantities to ship.

Figure 3 represents the flow of information and material in a civilian Point of Sale system. This flow differs somewhat from a military supply system in that an item sold in a retail store is not necessarily replaced in inventory, but may be substituted with a more salable item. Information flow in this system includes actual sales.

Figure 3 reflects only one warehouse operation, but in a real system warehouses could be strategically positioned throughout the country for cost efficient shipping. Day-to-day management tasks could employ the same telecommunication system used for processing orders.

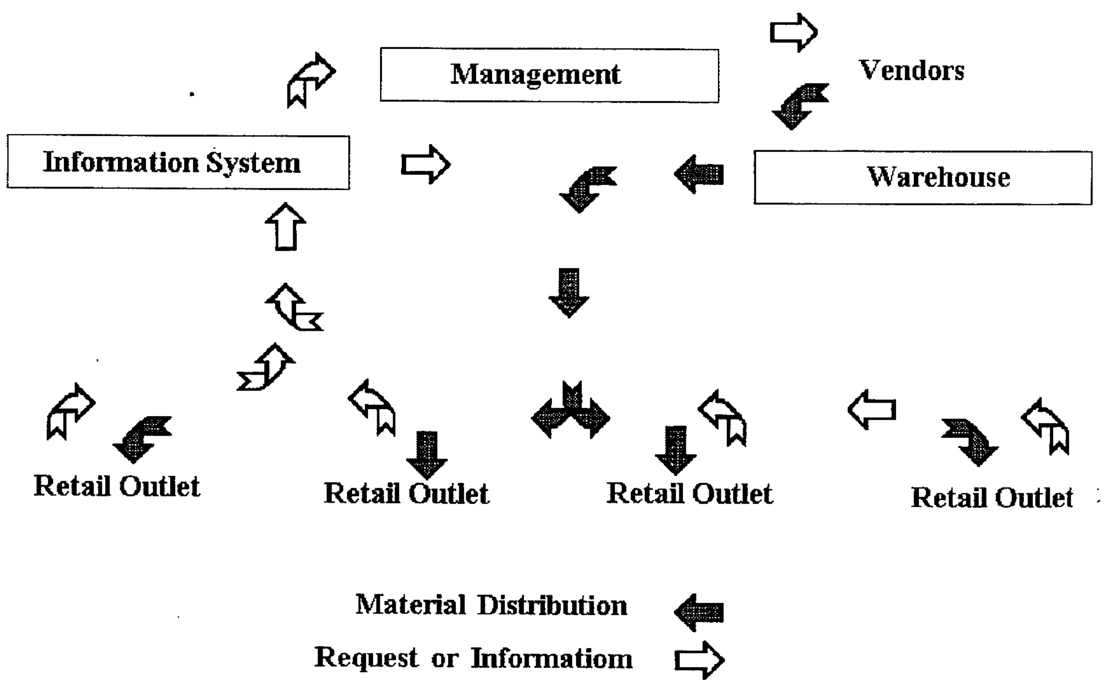

Figure 3. Flow of Information and Material in a Point of Sale System

In his article "Growing a Point of Sale System" [Ref. 6], Alan Morton lists many key features of Point of Sale systems. They include:

- Management information is standardized so the entire organization has access to it for decision making.
- If identical equipment is used in each outlet, this uniformity brings about the strategic advantage of being able to specialize the PCS application software to reflect the needs of the company. This can be done rapidly and the software can be passed over the same telecommunication system used for sales.
- Individual retailers can incorporate applications specific to their needs. An example would be retailers who are testing new lines of the company's products and require more detailed data for sales than outlets carrying the standard array of products.
- Because data input is done with a bar code scanner, the database used is much more accurate than would be the case in a manual entry system.
- Control of the operation is centralized and poor decision making is promulgated much more rapidly with the telecommunication system, but the same rapid communication provides the flexibility to correct the operation.
- Inventory can be managed more accurately by using historical sales data rather than by using orders which are often the best guess of the store managers.
- A key element of this system is the distribution aspect of the design. Distribution is performed on a need basis. These systems are not characterized by a company truck on a distribution route delivering fixed lots of items on a schedule. The key element that makes the point of sales systems possible, is the proliferation of the package delivery services like UPS and Federal Express.
- Because the company does not own its distribution system, it cannot place outlets anywhere. It must place them on the routes of the package delivery service.
- The company uses data gained from national sales to make decisions about its product line. This may lead to a situation where the company misses local trends for that product line.
- The speed of the information systems and delivery systems can lead to a situation, if not well managed, where the company is following short trends with the resulting accumulation of the cost inefficiencies that this would produce. An example is a clothing line which was only briefly popular being shipped widely to all the company's outlets.

C. AN ALTERNATE ARMY SUPPLY SYSTEM

The Army's version of a Point of Sale supply system would include the features listed under Point of Sale. The elements of using a bar code entry system for accuracy and a central information system for management, and a distribution system similar to the commercial operations of UPS or Federal Express would provide a very efficient supply system and meet the needs of the ROC Army. Figure 4 shows the flow of information and material in such a system. Differences between the current system and this alternate system occur in two features of any inventory system, the warehousing of the inventory, and communication. Currently, warehouses are at all levels in the hierarchy of maintenance and supply, and not as in a Point of Sale system. Additionally, communication in the current system is provided via paper documents and not via telecommunications. Much of the information in the current system, is not standardized, and is only available to management at that particular level of the bureaucracy.

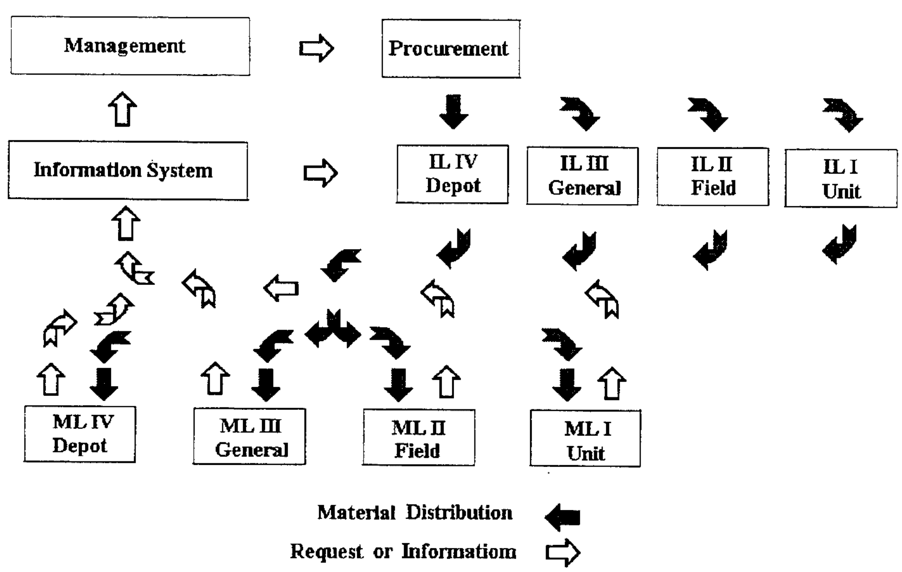

Figure 4. Flow of Information and Material in an Alternate System

D. MEASURE OF EFFECTIVENESS (MOE)

In order to determine whether the alternate system is better in terms of combat readiness, it is necessary to develop a MOE to compare the two systems. There are many factors which make up combat readiness or the effectiveness of a combat unit. These factors are interdependent. For the purposes of this study, operational readiness or operational availability will be used as a scale to differentiate between two supply systems: the current system and the alternate system. Operational readiness is a ratio of the amount of equipment expressed as a percentage, of equipment ready for use, versus the amount of equipment assigned to the unit.

$$operational\,readiness = \frac{number\,available\,for\,operations}{number\,assigned} \times 100$$

In the stochastic models of readiness, this percentage is directly related to

$$operational\,readiness = \frac{mean\,uptime\,for\,the\,unit}{mean\,uptime + mean\,downtime\,for\,the\,unit} \times 100 \qquad \textbf{(1)}$$

In the following chapters this measure (Equation 1) of operational readiness will provide an objective basis for evaluating various supply systems. The MOE shown in Equation 1 has an important characteristic. The uptime value appearing in both the numerator and denominator is a constant, independent of the choice of supply system. Choosing to maximize operational readiness *is the same* as choosing a supply system which minimizes mean downtime. In this thesis, however, we will stay with the Equation 1 version because of its operational meaning.

E. SUMMARY

This chapter has presented the three supply systems relevant to this thesis and explained some differences between the two systems under consideration, the current system and the alternate system proposed as its replacement. In the next chapter, an optimized model of the current supply system will be developed using the GAMS Program. This program will

generate the various probabilities of finding a part available at each level of the supply system. These probabilities will be used in Chapter IV to populate a decision tree for the purpose of quantifying the differences between the current supply system and its Point of Sale type of alternative.

III. MATHEMATICAL MODELS

To differentiate between the current supply system and an alternative system based on the civilian Point of Sale systems, it is useful to develop a mathematical model with which the two systems may be compared. This model will be used to represent both systems, and the results will be analyzed in the next chapter to provide a basis for the conclusions in the final chapter.

The primary difference in structure between the two supply systems is the time needed to request a part plus the time required for the part to be returned. In the alternative supply system, this time is represented by two links and in the current supply system this process may be represented by as many as ten links.

The performance of either supply system depends upon the availability of parts, and a comparison of different systems should be based upon the same values of the probabilities of parts being available. Then what set of probability values to use? There are many, and true values are unknown. In this chapter, the set of probability values will be found which permit the best performance of the current supply system. (Because of various constraints, these values cannot all be 1.0) These probabilities will be used in Chapter IV as the scenario in which the current supply system and the alternative supply system may be compared. The reason the best possible performance setting for the current supply system is sought, is that no data exists for the alternative supply system. Thus order to compare the two systems, a model is developed that compares the best possible current system against the alternative system using the same conditions.

In Section A of this chapter, the author will present an overview of stochastic modeling as it relates to the repair and support of equipment used by the Army battalion and a stochastic model that represents the equipment used by the battalion will be developed. This model is based on an alternating renewal process for the equipment, and will be used in Section B with the General Algebraic Modeling System (GAMS) Program and the topography of the current supply system to develop the needed values of the probabilities that a part will be available for the repair of equipment.

For this study only a battalion size unit will be considered. By using an infantry battalion as a typical unit, the model should be reasonably representative of the ROC Forces because the majority of units in the ROC are battalions, which are organized into infantry divisions and armored brigades. This will simplify the model by reducing the modeling requirements but should still provide a reasonably faithful representation of the supply systems' effect on unit readiness.

The constraints on the current supply system for purpose of this thesis are related to combat operations. Units that must deploy can only carry a limited weight or volume of supply support. At Inventory Levels III and Inventory Level IV, not involved in combat operations, there are constraints related to inventory volume. Without this constraint the most efficient supply system would be a system that provides unlimited support.

A. STOCHASTIC MODELING

This study will consider only three types or categories of equipment used in an infantry battalion. In this model, individual equipment requiring supply support will be represented by the category of that equipment rather than an individual item of equipment. Each piece of equipment entering the model will be represented by the parameters for that category of the equipment which are: failure rate, numbers assigned to unit, time to repair the equipment type at each maintenance level and supply time at each inventory level . The representation for the category of equipment is E_i and the indexed is by category where i=1, ... 3. [Ref. 4] These categories are based on the author's experience with ordnance equipment. Equipment E_1 is used to represent small arms, E_2 is heavy weapons, and E_3 is for vehicles.

1. Alternating Renewal Process

The modeling approach centers on the use of times represented by "uptime" when the equipment is functioning or ready to function, and available to the battalion, and "downtime" when the equipment is waiting for maintenance, undergoing repair, or waiting for parts from the supply system. A piece of equipment may be viewed as alternately experiencing "uptimes" and "downtimes." Let uptimes A_n, n=1,2,..., be independent and identically distributed continuous random variables with CDF $A(t)$ where variable t represents evaluation time. Let

downtimes B_n, n=1,2,..., be independent and continuously distributed random variables with CDF $B(t)$.

Assume $\{A_n, n=1,2,...\}$ and $\{B_n, n=1,2,...\}$ are independent. Here, the index n is the sequence number of a single cycle representing both the uptime and downtime as a single event where uptime is followed by downtime. [Ref. 7]

The system of each equipment E_i alternates being "up" and "down" independently and is shown in Figure 5. Let $T_n = A_n + B_n$, n=1,2,..., where T_n are the cycle time of the nth cycle. This is called an Alternating Renewal Process, with Cumulative Distribution Function (CDF): $T(t) = A(t) \times B(t)$. [Ref. 2]

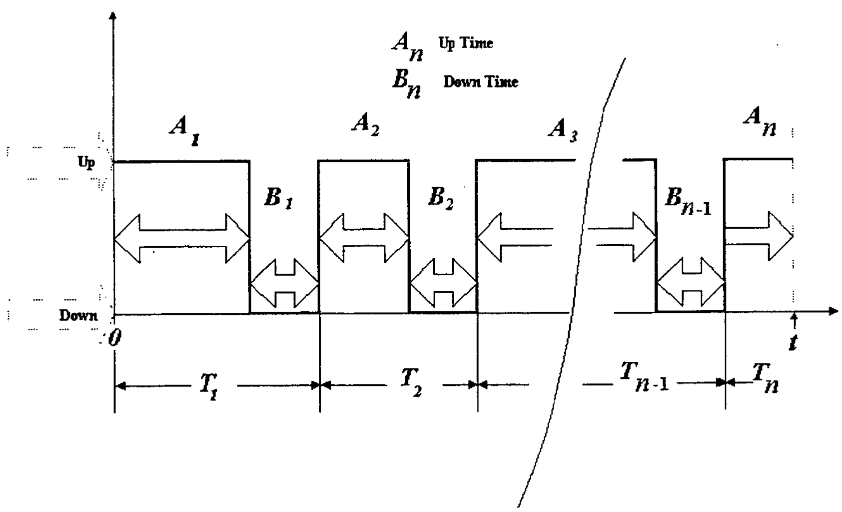

Figure 5. Uptime and Downtime

The four maintenance levels of the ROC Army are represented by maintenance level j where j= 1...4. Equipment failures may be categorized according to which of the four levels

of maintenance is required. The parameter $\lambda_{i,j}$ representing the failure rate of equipment type E_i at Maintenance Level j. Just as the normal distribution plays an important role in classical statistics because of the central limit theorem, the exponential distribution plays an important role in reliability and lifetime modeling since it is the only continuous distribution with a constant hazard function. Moreover, the exponential distribution is used because of its simplicity [Ref. 3]. Then

$$a_{i,j}(t) = \lambda_{i,j}\, e^{-\lambda_{i,j} t}, \quad t \geq 0 \tag{3}$$

is the Probability Density Function (PDF), and its Cumulative Distribution Function (CDF) is:

$$A_{i,j}(t) = \begin{cases} 1 - e^{-\lambda_{i,j} t}, & \text{if } t \geq 0 \\ 0, & \text{if } t < 0 \end{cases} \tag{4}$$

It is important to recognize here, that for a failure type, the random variable t represents <u>*operating time*</u> until failure. The clock or calendar time between consecutive failures of a given type may well exceed the value of the random variable t for that failure type. Item life may be described as the time until the first of any type of failure occurs. For each of the maintenance levels, the survival function is

$$\begin{aligned} S_{i,j}(t) &= 1 - A_{i,j}(t) \\ &= e^{-\lambda_{i,j} t}, \quad t \geq 0 \end{aligned} \tag{5}$$

If the functions in Equation 3 and Equation 4 are used to generate failures at rate $\lambda_{i,j}$ for equipment E_i, then the exponential distribution will have a mean of $\frac{1}{\lambda_{i,j}}$, which is Mean Time To Failure (*MTTF*) for equipment E_i of Maintenance Level j. Equipment Type i requiring Maintenance of Level j can be called or named $E_{i,j}$ equipment and its *MTTF* is:

$$MTTF \text{ of } E_{i,j} = E[A_{i,j}] = \frac{1}{\lambda_{i,j}} = \mu_{A_{i,j}}, \tag{6}$$

where $A_{i,j}$ is a random variable representing uptime of Equipment Type i at Maintenance Level j.

For this study, values are needed for the various failure rates. Table 1 is generated by the author from personal experience and will be used as failure rates per day for equipment E_i at Maintenance Level j. The representation in Table 1 is based upon the assumption that all items in an equipment category have the same set of failure rates, and that these failure rates will differ only because of the maintenance level required.

Table 1. Failure Rate of Equipment E_i at Maintenance Level $_j$

$\lambda_{i,j}$

	ML I	ML II	ML III	ML IV
E_1	1/60	1/120	1/280	1/3650
E_2	1/50	1/150	1/250	1/3650
E_3	1/30	1/160	1/210	1/2000

Equipment E_i is repaired at Maintenance Level j and supported at Supply Level or Inventory Level k. Equipment is repaired during the "downtime." The repair time is represented by $CO_{i,j}$ with a supply time of $CA_{i,k}$ and supply request time of $CA_{i,k}$ at Maintenance Level j where $j=1...4$ and Supply Level k where $k=1...5$. These supply times and repair times are assumed to be constants, and vary only with the supply level and Equipment Type i. Supply request time $CA_{i,k}$ is only modeled in the current system, and assumed to be zero for the alternative system that uses an information processing system.

The probability that parts are available for Maintenance Level j from Inventory Level k is $P_{i,j,k}$ where $j = 1,2,3,4$ *and* $k = 1,2,3,4,5$ for Equipment Type i where $i = 1,2,3$. A k index of five represents purchasing.

The CDF of time to failure A_i for equipment E_i is:

$$
\begin{aligned}
A_i(t) &= P(\,A_i \le t\,) \\
&= 1 - P\,(\,A_i \ge t\,) \\
&= 1 - P\,(\,A_{i,1} \ge t\,) \times P\,(\,A_{i,2} \ge t\,) \times P\,(\,A_{i,3} \ge t\,) \times P\,(\,A_{i,4} \ge t\,) \\
&= 1 - [\,1 - A_{i,1}(t)\,] \times [\,1 - A_{i,2}(t)\,] \times [\,1 - A_{i,3}(t)\,] \times [\,1 - A_{i,4}(t)\,] \\
&= 1 - e^{\lambda_{i,1}\,t} \times e^{\lambda_{i,2}\,t} \times e^{\lambda_{i,3}\,t} \times e^{\lambda_{i,4}\,t} \\
&= 1 - e^{(\lambda_{i,1}+\lambda_{i,2}+\lambda_{i,3}+\lambda_{i,4})\,t} \quad ,
\end{aligned}
\tag{7}
$$

where:

A_i = time to failure of E_i, $i = 1, 2, 3$

= minimum ($A_{i,1}$, $A_{i,2}$, $A_{i,3}$, $A_{i,4}$),

$A_{i,1}$ = time to failure of equipment E_i subject to Maintenance Level *I* service,

$A_{i,2}$ = time to failure of equipment E_i subject to Maintenance Level *II* service,

$A_{i,3}$ = time to failure of equipment E_i subject to Maintenance Level *III* service,

$A_{i,4}$ = time to failure of equipment E_i subject to Maintenance Level *IV* service,

and where $A_i \sim A_i\,(t)$.

An overall time to failure of equipment E_i with an uptime of A_i has an exponential distribution with parameters $\lambda_{i,1} + \lambda_{i,2} + \lambda_{i,3} + \lambda_{i,4}$. For simplification, repair time and respective supply times are included with the downtime of equipment E_i.

2. Availability

Availability, in this study is defined as the sum of the availabilities of each of the three types of equipment, which in each case is the time the equipment is ready for use or uptime, divided by the time that the equipment is ready for use(uptime) plus the time that the equipment cannot be used or downtime. The Measure of Effectiveness (MOE) for this thesis will consist of the availability as described and is a direct result of the effects of Mean Time to Failure (MTTF) and the Mean Time to Repair (MTTR) a particular type of equipment assigned to the battalion. This thesis addresses specifically the inventory systems' effect on the MTTR of the equipment.

The availability of equipment type E_i is shown in Equation 8. Assuming all of the equipment is in "up" at time 0. The *MTTF*, μ_{A_i} is the expected value of A_i for equipment i that was provided by author in Table 1 as *MTTFs* reciprocal, failure rate. Thus,

$$AVAILABILITY = \frac{\mu_{A_i}}{\mu_{A_i} + \mu_{B_i}}, \quad \forall i \quad , \qquad \textbf{(8)}$$

where:

μ_{A_i} = MTTF or expected uptime of equipment E_i in t days, or

$$\begin{aligned} \mu_{A_i} &= E[A_i] \\ &= - \; t \; e^{(\lambda_{i,1}+\lambda_{i,2}+\lambda_{i,3}+\lambda_{i,4}) \; t}\Big|_0^\infty + \int_0^\infty e^{(\lambda_{i,1}+\lambda_{i,2}+\lambda_{i,3}+\lambda_{i,4}) \; t} \\ &= \frac{1}{\lambda_{i,1}+ \lambda_{i,2}+ \lambda_{i,3}+ \lambda_{i,4}} \quad , \quad \forall i \quad , \quad and \end{aligned} \qquad \textbf{(9)}$$

μ_{B_i} = Mean Time to Repair or expected downtime of equipment E_i in t days.

The current supply systems can be modeled with the following equations using B_i to represent equipment type E_i's downtime:

$$\begin{aligned} \mu_{B_i} &= E \; [Downtime \;\; of \; E_i \;\; in \;\; t \;\; days] \\ &= \sum_{j=1}^{4} B_{i,j} \times \frac{\lambda_{i,j}}{\sum_{j=1}^{4} \lambda_{i,j}} \quad ,\forall \; i \quad , \end{aligned} \qquad \textbf{(10)}$$

here $B_{i,j}$ is downtime for Equipment Type i at Maintenance Level j. Equation 10 represents the failure rate for Equipment Type i at Maintenance Level j as a ratio of the equipment's combined failure rates for all maintenance levels.

By adding the topography of the current system, we have

$$\begin{aligned}
\mu_{B_i} = {} & [\ CO_{i,1} + \sum_{k=1}^{1}(CA_{i,k} + C_{i,k})\times P_{i,1,1} + \sum_{k=1}^{2}(CA_{i,k} + C_{i,k})\times P_{i,1,2} \\
& + \sum_{k=1}^{3}(CA_{i,k} + C_{i,k})\times P_{i,1,3} + \sum_{k=1}^{4}(CA_{i,k} + C_{i,k})\times P_{i,1,4} \\
& + \sum_{k=1}^{5}(CA_{i,k} + C_{i,k})\times P_{i,1,5}\ ] \times \frac{\lambda_{i,1}}{\sum_{j=1}^{4}\lambda_{i,j}} \\
& + [\ CO_{i,2} + \sum_{k=2}^{2}(CA_{i,k} + C_{i,k})\times P_{i,2,2} + \sum_{k=2}^{3}(CA_{i,k} + C_{i,k})\times P_{i,2,3} \\
& + \sum_{k=2}^{4}(CA_{i,k} + C_{i,k})\times P_{i,2,4} + \sum_{k=2}^{5}(CA_{i,k} + C_{i,k})\times P_{i,2,5}\ ] \times \frac{\lambda_{i,2}}{\sum_{j=1}^{4}\lambda_{i,j}} \\
& + [\ CO_{i,3} + \sum_{k=3}^{3}(CA_{i,k} + C_{i,k})\times P_{i,3,3} + \sum_{k=3}^{4}(CA_{i,k} + C_{i,k})\times P_{i,3,4} \\
& + \sum_{k=3}^{5}(CA_{i,k} + C_{i,k})\times P_{i,3,5}\ ] \times \frac{\lambda_{i,3}}{\sum_{j=1}^{4}\lambda_{i,j}} \\
& + [\ CO_{i,4} + \sum_{k=4}^{4}(CA_{i,k} + C_{i,k})\times P_{i,4,4} + \sum_{k=4}^{5}(CA_{i,k} + C_{i,k})\times P_{i,4,5}\ ] \times \frac{\lambda_{i,4}}{\sum_{j=1}^{4}\lambda_{i,j}},\ \forall i
\end{aligned} \quad \textbf{(11)}$$

where:

$CO_{i,j}$ = the constant time for the repair of equipment type E_i at Maintenance Level j,

$C_{i,k}$ = supply time in days for Equipment Type i at Supply Level k,

$CA_{i,k}$ = request time in days for Equipment Type i at Supply Level k, and

$P_{i,j,k}$ = the probability that the needed repair part for Maintenance Level j is available on Inventory Level k for Equipment Type i.

The alternate supply systems can be modeled with the following equations using B_i to represent equipment type E_i's downtime. Have,

$$\begin{aligned}\mu_{B_i} &= E\ [Downtime\ \ of\ E_i\ \ in\ \ t\ \ days] \\ &= \sum_{j=1}^{4} B_{i,j} \times \frac{\lambda_{i,j}}{\sum_{j=1}^{4} \lambda_{i,j}} \quad , \quad \forall\ i \quad ,\end{aligned} \tag{12}$$

or by adding the topography of the alternative system:

$$\begin{aligned}\mu_{B_i} = &\ [\ CO_{i,1} + C_{i,1} \times P_{i,1,1} \\ &+ (\ C_{i,1} + C_{i,2}\ ) \times P_{i,1,2} \\ &+ (\ C_{i,1} + C_{i,3}\ ) \times P_{i,1,3} \\ &+ (\ C_{i,1} + C_{i,4}\ ) \times P_{i,1,4} \\ &+ (\ C_{i,1} + C_{i,5}\ ) \times P_{i,1,5}\ ] \times \frac{\lambda_{i,1}}{\sum_{j=1}^{4} \lambda_{i,j}} \\ &+ [\ CO_{i,2} + C_{i,2} \times P_{i,2,2} \\ &+ (\ C_{i,2} + C_{i,3}\ ) \times P_{i,2,3} \\ &+ (\ C_{i,2} + C_{i,4}\ ) \times P_{i,2,4} \\ &+ (\ C_{i,2} + C_{i,5}\ ) \times P_{i,2,5}\ ] \times \frac{\lambda_{i,2}}{\sum_{j=1}^{4} \lambda_{i,j}} \\ &+ [\ CO_{i,3} + C_{i,3} \times P_{i,3,3} \\ &+ (\ C_{i,3} + C_{i,4}\ ) \times P_{i,3,4} \\ &+ (\ C_{i,3} + C_{i,5}\ ) \times P_{i,3,5}\ ] \times \frac{\lambda_{i,3}}{\sum_{j=1}^{4} \lambda_{i,j}} \\ &+ [\ CO_{i,4} + C_{i,4} \times P_{i,4,4} \\ &+ (\ C_{i,4} + C_{i,5}\ ) \times P_{i,4,5}\ ] \times \frac{\lambda_{i,4}}{\sum_{j=1}^{4} \lambda_{i,j}} \quad , \quad \forall\ i \quad ,\end{aligned} \tag{13}$$

where:

$C0_{i,j}$ = the constant time for the repair of equipment type E_i at Maintenance Level j,

$C_{i,k}$ = supply time in days for Equipment Type i at Supply Level k, and

$P_{i,j,k}$ = the probability that the needed repair part for Maintenance Level j is available on Inventory Level k for Equipment Type i.

For these formulations to be useful, the author has used his experience to generate probable mean repair and supply times for the battalion's equipment. These times are shown in Table 2 and Table 3.

Table 2. Estimated Repair Time, $C0_{i,j}$, for Equipment E_i in Days

	ML I	*ML II*	*ML III*	*ML IV*
E_1	0.5	3	15	180
E_2	2	5	20	200
E_3	3	6	30	240

Table 3. Estimated Supply Time for Equipment E_i in Days

	IL I		*IL II*		*IL III*		*IL IV*		*Purchasing*	
	CA	*C*	*CA*	*C*	*CA*	*C*	*CA*	*C*	*CA*	*C*
E_1	1	4	7	10	5	15	7	15	90	90
E_2	1	4	7	12	5	20	7	20	120	120
E_3	1	3	7	15	5	25	7	25	100	90

3. Approximating Parts

The approximate number of needed parts to repair equipment E_i is required to provide constraints for the GAMS Model in Section B of this chapter. These restraints are related to available inventory space, and the carrying capacity of the battalion. The number of parts generated in Table 4 is calculated from the number of equipment assigned to the infantry battalion. The numbers of equipment, weight and volume of parts are based on the author's experience and are representative of those for the equipment assigned to the

battalion, and are shown in Table 5 and Table 6. Carrying weight is applicable to the mobility levels of the supply units.

Table 4. Numbers of Equipment and Parts Required on Each Maintenance or Repair for E_i

		E_1	E_2	E_3
Numbers of Equipment		500	60	30
Unit Inventory Volume (m^3)		0.01	0.03	0.02
Unit Weight (kg)		0.02	0.10	0.10
Repair Parts Required per Failure	***ML I***	4	7	10
	ML II	10	15	40
	ML III	15	30	150
	ML IV	60	150	1000

Table 5. Inventory Space and Carrying Capacity

	Inventory Space m^3	**Carrying Capacity kg**
ML I	200	300
ML II	500	800
ML III	1000	NA
ML IV	5000	NA

The stochastic systems evolution through time was interspersed with renewals or regeneration times when, in a statistical sense, the process began anew. The Alternating Renewal (counting) Process $\{N(t), t \geq 0\}$ is a nonnegative integer-valued stochastic process that registers the successive occurrences of an event during the time interval $(0, t)$, where the time durations between consecutive events are positive, independent, identically distributed random variables. Let,

$$m(t) = E[N(t)] \quad , \tag{14}$$

and the expected number of renewals for the time duration $(0,t)$ is

$$m(t) \approx \frac{t}{\mu} + \frac{\sigma^2 - \mu^2}{2\,\mu^2} \; . \tag{15}$$

and by removing the second term of Equation 15, which is not significant for large values of t, then it follows that:

$$m(t) \approx \frac{t}{\mu} \quad , \; for \; large \; t \quad , \tag{16}$$

where μ is the expected value of one renewal cycle and $m(t)$ is the approximate number of parts needed.

The approximate number of parts needed for equipment E_i in t days can be calculated as follows assuming that the mean uptime A_i and the mean downtime B_i are independent:

$$\mu_i = \mu_{A_i} + \mu_{B_i} \quad , \tag{17}$$

$$\sigma_i^2 = \sigma_{A_i}^2 + \sigma_{B_i}^2 \quad . \tag{18}$$

Because we assume A_i and B_i are independent, but, all of the B_i 's are composed of constant time, i.e. $\sigma_{B_i}^2 = 0$, so,

$$\sigma_i^2 = \sigma_{A_i}^2 \ , \tag{19}$$

where:

μ_i = sum of the expected values of uptime A_i and downtime B_i for equipment E_i,

σ_i^2 = sum of the variance of the uptime A_i and downtime B_i in days squared,

$\sigma_{A_i}^2$ = variance of uptime A_i in days squared,

$\sigma_{B_i}^2$ = variance of downtime B_i in days squared, and

$m(t)_{i,j}$ = approximate number of parts needed to repair equipment E_i on Maintenance Level j in t days.

Table 6 is the calculated results.

Table 6. Approximate Number of Parts Needed for E_i

t = 365 Days		E_1	E_2	E_3
$m(t)_{i,j}$	*ML I*	11184	3594	2996
	ML II	14102	3385	3385
	ML III	8694	2783	5217
	ML IV	1451	581	1451

B. NON-LINEAR MODEL

In order to find the $P_{j,k}$ values, we will solve a non-linear programming problem which reflects the various constraints. The objective function in Equation 20 is to maximize availability for the current supply system. The given data consists of the failure rate of the equipment, the constant time needed to repair equipment, various constant supply times which

represent requesting parts and the return of parts to the repair facility. Other data are the volume and weight limitation at various supply levels. Additionally, the author will explain later in this section the difference constant which is used to ensure that all three types of equipment are supported at every supply level.

The constraints consist of the probability that a needed part will be available for maintenance at any particular maintenance level. All probabilities for any particular maintenance level to the supply level that is the source for a part, must equal 1. Equation 27 is a constraint related to inventory space and Equation 28 is a constraint related to Inventory Level I and Inventory Level II of supply and is a constraint of carrying capacity for mobile units.

1. Indices

The indices for the non-linear model are the type of equipment, maintenance level and the inventory or supply level to support the equipment. They are represented and their ranges are as follows:

i = equipment category index, $i = 1,2,3$,

j = Maintenance Level, j=1,2,3,4, and

k = Supply Level, k =1,2,3,4,5.

2. Given Data

A variety of information is needed in this problem. Values will be used for the following given data:

$\lambda_{i,j}$ = failure rate of E_i at $ML\, j$ in days,

$C0_{i,j}$ = the constant time for the repair of equipment type E_i at Maintenance Level j,

$C_{i,k}$ = supply time in days for Equipment Type i at Supply Level k,

$CA_{i,k}$ = request time in days for Equipment Type i at Supply Level k,

μ_{A_i} = mean "uptime" in days,

$UV_{i,j}$ = average unit volume of parts of E_i in m^3 ,

$IV_{i,j}$ = limit of inventory volume of E_i on Maintenance Level j in m^3,

$UW_{i,j}$ = average unit weight of parts of E_i on Maintenance Level j in kg,

$CW_{i,j}$ = limit of carry capacity of E_i on Maintenance Level j in kg,

$N_{i,j}$ = number of parts we can expect to need for E_i from Maintenance Level j in t, and

D= the difference between the probabilities of parts being available for the repair of any equipment type at the 4 maintenance levels.

3. Decision Variable

In this problem there are a set of decision variables which include:

μ_{B_i} = mean "downtime" in days,

$P_{j,k}$ = the probability that the needed repair part for maintenance level j is available on Inventory Level k for the repair of all equipment types,

$PL_{j,k}$ = the binomial probability that the needed repair part for maintenance level j is available on Inventory Level k for the repair of all equipment types, and

$R_{j,k}$ = used to maintain the same values among the probability of repair parts available for any equipment type on Maintenance Level j and Supply Level k.

4. Formulations

The optimization problem is as follows:

$$\text{Maximize Availability} = \sum_{i=1}^{3} \frac{\mu_{A_i}}{\mu_{A_i} + \mu_{B_i}}, \tag{20}$$

subject to

$$P_{j,1} = PL_{j,1}, \quad \forall j, \tag{21}$$

$$P_{j,2} = (1-PL_{j,1}) \times PL_{j,2}, \ \forall j, \tag{22}$$

$$P_{j,3} = (1-PL_{j,1}) \times (1-PL_{j,2}) \times PL_{j,3}, \quad \forall j, \tag{23}$$

$$P_{j,4} = (1-PL_{j,1}) \times (1-PL_{j,2}) \times (1-PL_{j,3}) \times PL_{j,4}, \ \forall j, \tag{24}$$

$$P_{j,5} = (1-PL_{j,1}) \times (1-PL_{j,2}) \times (1-PL_{j,3}) \times (1-PL_{j,4}), \quad \forall j, \tag{25}$$

$$\sum_{k=j}^{5} P_{j,k}=1 \ , \ \forall\, j \quad , \tag{26}$$

$$\sum_{i=1}^{3} \sum_{k=1}^{j} (N_{i,j} \times P_{j,k} \times UV_{i,j}) \le IV_j \quad ,\forall j \quad , \tag{27}$$

$$\sum_{i=1}^{3} \sum_{k=1}^{j} (N_{i,j} \times P_{j,k} \times UW_{i,j}) \le CW_j \quad , j=1,2 \ , \tag{28}$$

$$PL_{j,k} - R_{j,k} = D \quad , \forall\, j,k \quad , \tag{29}$$

$$\begin{aligned}
\mu_{B_i} = {} & [\ C0_{i,1} + \sum_{k=1}^{1} (CA_{i,k} + C_{i,k}) \times P_{1,1} + \sum_{k=1}^{2} (CA_{i,k} + C_{i,k}) \times P_{1,2} \\
& + \sum_{k=1}^{3} (CA_{i,k} + C_{i,k}) \times P_{1,3} + \sum_{k=1}^{4} (CA_{i,k} + C_{i,k}) \times P_{1,4} \\
& + \sum_{k=1}^{5} (CA_{i,k} + C_{i,k}) \times P_{1,5}\ ] \times \frac{\lambda_{i,1}}{\sum_{j=1}^{4} \lambda_{i,j}} \\
& + [\ C0_{i,2} + \sum_{k=2}^{2} (CA_{i,k} + C_{i,k}) \times P_{2,2} + \sum_{k=2}^{3} (CA_{i,k} + C_{i,k}) \times P_{2,3} \\
& + \sum_{k=2}^{4} (CA_{i,k} + C_{i,k}) \times P_{2,4} + \sum_{k=2}^{5} (CA_{i,k} + C_{i,k}) \times P_{2,5}\ ] \times \frac{\lambda_{i,2}}{\sum_{j=1}^{4} \lambda_{i,j}} \\
& + [\ C0_{i,3} + \sum_{k=3}^{3} (CA_{i,k} + C_{i,k}) \times P_{3,3} + \sum_{k=3}^{4} (CA_{i,k} + C_{i,k}) \times P_{3,4} \\
& + \sum_{k=3}^{5} (CA_{i,k} + C_{i,k}) \times P_{3,5}\ ] \times \frac{\lambda_{i,3}}{\sum_{j=1}^{4} \lambda_{i,j}} \\
& + [\ C0_{i,4} + \sum_{k=4}^{4} (CA_{i,k} + C_{i,k}) \times P_{4,4} + \sum_{k=4}^{5} (CA_{i,k} + C_{i,k}) \times P_{4,5}\ ] \times \frac{\lambda_{i,4}}{\sum_{j=1}^{4} \lambda_{i,j}} \ , \ \forall i \ ,
\end{aligned} \tag{30}$$

where

$$0 \le PL_{j,k} \le 1, \forall j, k,$$
$$0 \le R_{j,k} \le 1, \forall j,k, \text{ and}$$
$$0 \le P_{j,k} \le 1, \forall j, k.$$

The objective of this program is to maximize the sum of the availabilities of E_is with the above constraints. Without these constraints the model would create maximum availability of parts at the lowest supply level in order to maximize the availabilities of E_is. By setting upper and lower boundaries for the probability of available parts at each supply level a more realistic model is created. For example, if we set the lower bounds of the probability for Level V at .05, then this is a probability of obtaining parts from Supply Level V or purchasing the parts from suppliers because they are not available in any of the lower levels of the system. The supply level is initialized at the lower bound of the probability and not allowed to raise beyond the upper bound of 1.0. The total probability of a part being available for all supply levels must equal 1.0.

Table 7. Lower Boundaries of Parts Availability Probabilities

Procurement to Required Maintenance Level	$PL_{1,5}$	$PL_{2,5}$	$PL_{3,5}$	$PL_{4,5}$
Probability Lower Bound	0.05	0.10	0.15	0.30

The probability that a part will be available at any supply level is the sum of the probability at that level plus the probability for the levels above. An example is that the probability of a part being available at Supply Level I is the probability of a part being available anywhere from Supply Level I to Supply Level V or purchasing, but the probability of a part being available at Supply Level II is only from Supply Level II to purchasing.

It was necessary to create a variable ($R_{j,k}$) as an inventory ratio between inventory levels. This forced the probabilities for all equipment types to a common value difference by the value D, and produced a more realistic model. Without this ratio ($R_{j,k}$) and difference value (D) the equipment that was used by the battalion in very small quantities would be

forced to an upper level for support because the single variable measurement of readiness would not be affected significantly by the equipment type.

Listed in Table 8 are the results of GAMS Program. It can be seen in the table that most support for the equipment in the battalion must originate from Inventory Levels j=I and j=II to achieve optimal availability. The purchase level or Level V values have been added to the values in Table 8 and represent the author's experience at a depot level maintenance facility. Only one type of equipment is shown in the table, but the values are the same for all three types of equipment in the model.

Table 8. Optimized Probabilities $P_{j,k}$ from Supply Levels k to Maintenance Level j for All Equipment

$P_{j,k}$					
	k=I	*k=II*	*k=III*	*k=IV*	*k=V*
j=I	0.34	0.61	0	0	0.05
j=II	-	0.16	0.74	0	0.10
j=III	-	-	0.57	0.28	0.15
j=IV	-	-	-	0.70	0.30

C. SUMMARY

The optimized probabilities generated with the GAMS Program for the decision variable $P_{j,k}$ will be used to model both the current system and the proposed alternative. This variable represents the probability of a repair part being available for all equipment types at Maintenance Level j from Supply Level k. This probability and the constants that represent repair time and supply time at each level and the topography or each supply system can be used to determine the readiness of the example infantry battalion. In Chapter IV, a model is constructed using these optimum probabilities to represent the current supply system and a

proposed alternative. The results generated from this model are analyzed and will be used as a basis for the author's conclusions and recommendations in the final chapter.

IV. COMPARISON OF THE TWO SUPPLY SYSTEMS

This chapter will populate a decision tree using the optimized probabilities generated with the GAMS Program in Chapter III. The decision tree is a tool used to analyze the developed models [Ref. 5]. This decision tree will be used to evaluate the two supply systems and test the sensitivity of the decision to the variables used in the tree.

Section A of the chapter will introduce the decision tree to the reader together with the symbology used in decision trees. In Section B, the trees developed for this study are presented for the current and alternative supply systems. In Section C, a sensitivity analysis is performed on several variables to ascertain their effects on the model. In the final section of the chapter, the results of the sensitivity analysis are presented.

A. ESSENTIAL ELEMENTS

The decision tree developed in the approach used in this chapter use nodes and branches.

1. Nodes

There are three types of nodes:

- Decision Nodes (square nodes),
- Chance Nodes, Random events or Quantities (round nodes), and
- Result Nodes which are the results of the decision process (diamond nodes).

Decision Nodes represent two or more decisions followed by branches of the decision trees. Decision nodes results are based on either a maximized or a minimized function. In DATA Software this is indicated by a square node with either a down arrow for minimized result or an up arrow for maximized result.

Chance Nodes represent random quantities with a probability distribution on two or more branches. This distribution in most cases is derived from the probabilities generated in Chapter III with the GAMS Program.

Result Nodes (or as called in the DATA Program, Payoffs) are set in the decision tree developed in the chapter for the maintenance time, supply request time and supply time corresponding to various Maintenance and Supply Levels for each Equipment Type, using values developed in Chapter III.

2. Branches in Decision Tree

Branches represent passable outcomes of the nodes for decision nodes and chance nodes. All decision and chance nodes lead through their branches to a result node. When branches come from a decision node, they represent alternatives for that decision.

B. THE DECISION SAPLING

We will use the stochastic model developed in Chapter III demonstrate the essential elements of the decision between the two supply systems. Here, the uncertainty outcomes B represent downtimes, and the potentially payoffs of an alternative supply system will be better or equal to the current system. The decision tree for this problem is shown in Figure 6 and Figure 7. In Figure 6 and Figure 7 each supply system has four branches made up of probabilities of a failure of equipment at that maintenance level. In terminology of this system (DATA for Windows) this is called a decision sapling [Ref. 5].[1]

Figure 6 and Figure 7 depict the the decision trees. These trees are made up of the sum of the probabilities of a piece of equipment being subject to maintenance at that particular maintenance level. The round nodes indicate that the model will produce the expected value

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[1] The DATA for Windows Software was selected because it provides a graphics output for sensitivity analysis which simplifies the task of analyzing the difference between the current supply system and the alternative supply system. An overall picture of the model can be gained by examining the decision tree constructed by the author to represent both systems. The system was particularly user-friendly and that the tree is constructed by using the mouse to assemble the user's visualization of the model.

for the branches leading to that node. Each piece of equipment's downtime is made up of downtime for that equipment at each maintenance level.

Minimized expected downtime in this model is used to represent a maximize availability of the equipment. The probabilities at this level of the current and alternative decision trees are identical and represent the MTTFs for the three types of equipment used by the battalion. They are:

$$PrML_j = \frac{\lambda_{i,j}}{\sum_{j=1}^{4} \lambda_{i,j}} \quad ,\forall\ i \quad , \tag{31}$$

where parameter $\lambda_{i,j}$ represents the failure rate of equipment type E_i at Maintenance Level j.

Figure 6 represents the current supply system. The WD values at the far branches of the decision tree are the constants used in Chapter III to represent repair time and supply time at the various maintenance levels of the current system. In terms of Data Program this is termed a "Payoff." The round nodes at the intermediate branching positions of the tree are set to employ the optimized probabilities calculated in Chapter III for that supply level for a part being available to repair that equipment type. In Figure 6 the arrangement of the tree represents a system where when a part is not available the part will be requested in a cascading arrangement from the supply level above.

Figure 7 is the tree that represents the alternative supply system. The essential difference between the alternative and current system is the arrangement of the round nodes. In the alternative system the probability of a part being available for the repair of the three types of equipment used by the battalion, is the expected probability of a part being available at any level of the supply system.

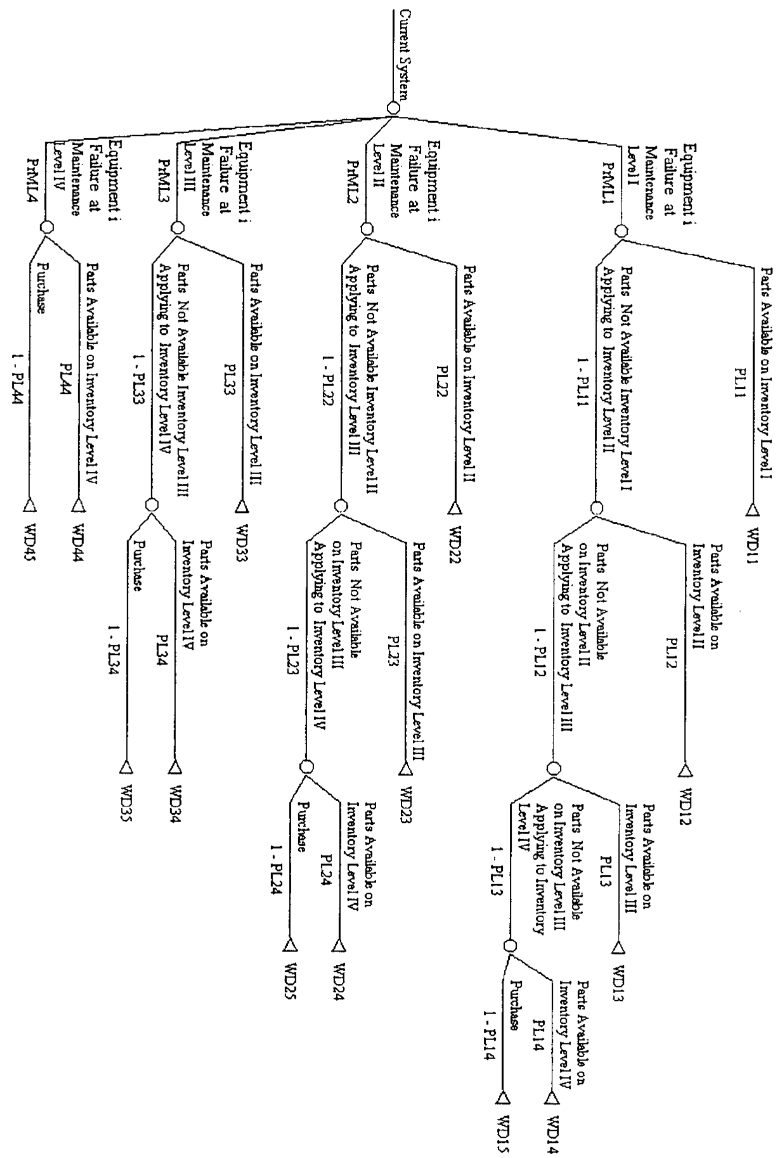

Figure 6. Current System Decision Tree

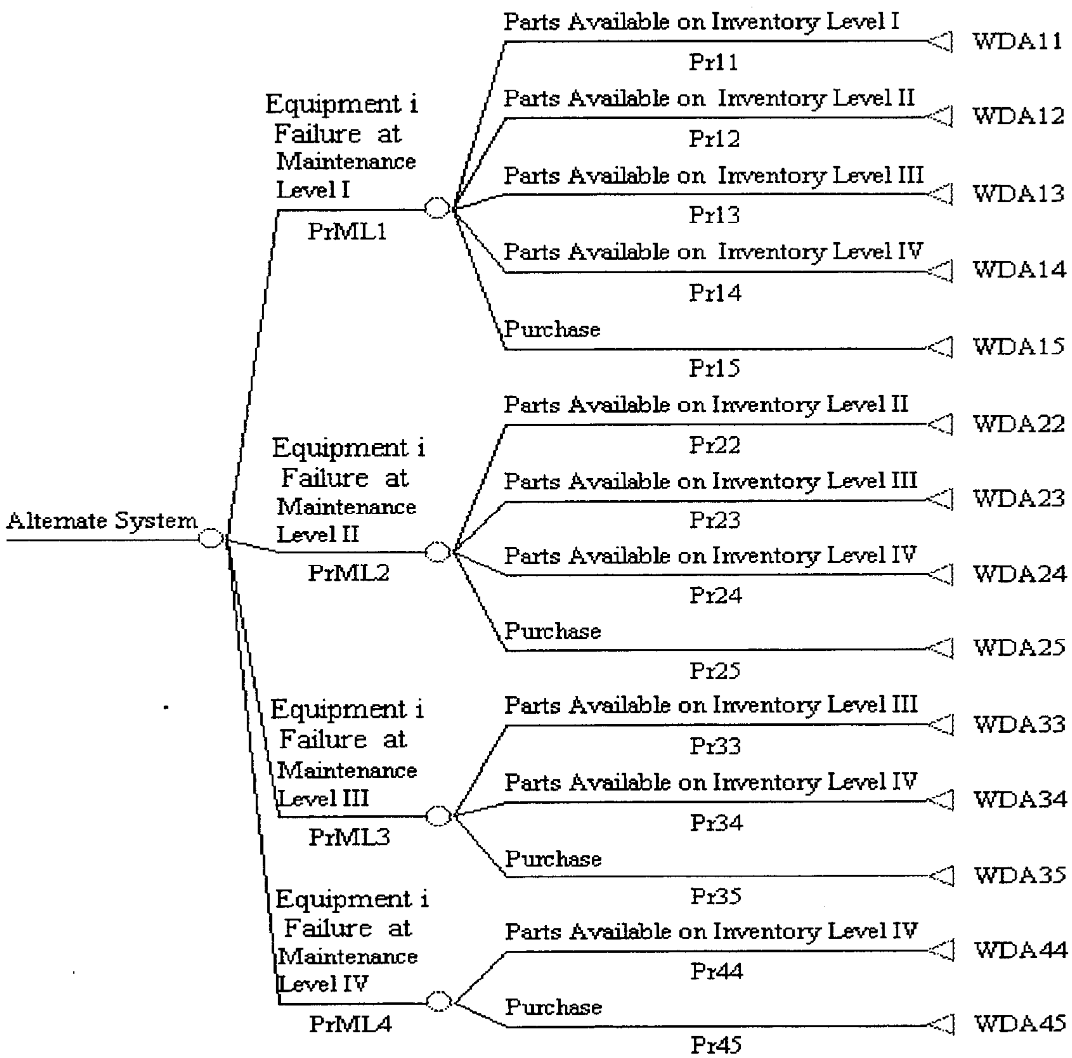

Figure 7. Alternative System Decision Tree

Table 9 gives definitions of the variables used throughout the entire decision tree. The WD variables are defined for both the alternative system and the current system to represent the constants at that level of each system.

TABLE 9. Variables in Decision Tree

Variable	Definition
C01 = 0.5	The constant time for the repair of equipment type E_1 at Maintenance Level I
C02 = 3	The constant time for the repair of equipment type E_1 at Maintenance Level II
C03 = 15	The constant time for the repair of equipment type E_1 at Maintenance Level III
C04 = 180	The constant time for the repair of equipment type E_1 at Maintenance Level IV
C1 = 4	Supply time in days from Inventory Level I and the corresponding maintenance level to Inventory Level II
C2 = 10	Supply time in days from Inventory Level II and the corresponding maintenance level to Inventory Level III
C3 = 15	Supply time in days from Inventory Level III and the corresponding maintenance level to Inventory Level IV
C4 = 15	Supply time in days from Inventory Level IV and the corresponding maintenance level to Purchasing
C5 = 90	Supply time in days at Purchasing
CA1 =1	Supply request time in days from Maintenance Level I to Inventory Level I
CA2 = 7	Supply request time in days from Maintenance Level II to Inventory Level II
CA3 = 5	Supply request time in days from Maintenance Level III to Inventory Level III
CA4 = 7	Supply request time in days from Maintenance Level IV to Inventory Level IV

CA5 = 90	Supply request time in days to Purchasing Maintenance Level IV
LA1 =1/ 60	Failure rate of equipment E_1 per day on Maintenance Level I
LA2 = 1/120	Failure rate of equipment E_1 per day on Maintenance Level II
LA3 = 1/280	Failure rate of equipment E_1 per day on Maintenance Level III
LA4 = 1/3650	Failure rate of equipment E_1 per day on Maintenance Level IV
PL11 = 0.34	Probability that the needed repair part is available for equipment E_1 on Supply Level I for Maintenance Level I
PL12 = 0.92	Probability that the needed repair part is available for equipment E_1 on Supply Level II for Maintenance Level I
PL13 = 0	Probability that the needed repair part is available for equipment E_1 on Supply Level III for Maintenance Level I
PL14 = 0	Probability that the needed repair part is available for equipment E_1 on Supply Level IV for Maintenance Level I
PL15 = 1	Probability that the needed repair part is available for equipment E_1 on Supply Level V for Maintenance Level I
PL22 = 0.16	Probability that the needed repair part is available for equipment E_1 on Supply Level II for Maintenance Level II
PL23 = 0.88	Probability that the needed repair part is available for equipment E_1 on Supply Level III for Maintenance Level II
PL24 = 0	Probability that the needed repair part is available for equipment E_1 on Supply Level IV for Maintenance Level II
PL25 = 1	Probability that the needed repair part is available for equipment E_1 on Supply Level V for Maintenance Level II
PL33 = 0.57	Probability that the needed repair part is available for equipment E_1 on Supply Level III for Maintenance Level III

PL34 = 0.65	Probability that the needed repair part is available for equipment E_1 on Supply Level IV for Maintenance Level III
PL35 = 0.05	Probability that the needed repair part is available for equipment E_1 on Supply Level V for Maintenance Level III
PL44 = 0.7	Probability that the needed repair part is available for equipment E_1 on Supply Level IV for Maintenance Level IV
PL45 = 0.3	Probability that the needed repair part is available for equipment E_1 on Supply Level V for Maintenance Level IV
PrML1 = LA1 /(LA1+LA2+LA3+LA4)	Probability that equipment E_1 will be subject to maintenance at Maintenance Level I
PrML2 =LA2 /(LA1+LA2+LA3+LA4)	Probability that equipment E_1 will be subject to maintenance at Maintenance Level II
PrML3 =LA3 /(LA1+LA2+LA3+LA4)	Probability that equipment E_1 will be subject to maintenance at Maintenance Level III
PrML4 =LA4 /(LA1+LA2+LA3+LA4)	Probability that equipment E_1 will be subject to maintenance at Maintenance Level IV
WD11=C01+C1	Constant Payoff for Supply Level I to Maintenance Level I for the Current System
WD12=C01+C1+C2	Constant Payoff for Supply Level II to Maintenance Level I for the Current System
WD13=C01+C1+C2+C3	Constant Payoff for Supply Level III to Maintenance Level I for the Current System
WD14=C01+C1+C2+C3+C4	Constant Payoff for Supply Level IV to Maintenance Level I for the Current System
WD15=C01+C1+C2+C3+C4+C5	Constant Payoff for Supply Level V to Maintenance Level I for the Current System
WD22=C02+C1	Constant Payoff for Supply Level II to Maintenance Level II for the Current System
WD23=C02+C1+C3	Constant Payoff for Supply Level III to Maintenance Level II for the Current System

WD24=C02+C1+C3+C4	Constant Payoff for Supply Level IV to Maintenance Level II for the Current System
WD25=C02+C1+C3+C4+C5	Constant Payoff for Supply Level V to Maintenance Level II for the Current System
WD33=C03+C1	Constant Payoff for Supply Level III to Maintenance Level III for the Current System
WD34=C03+C1+C4	Constant Payoff for Supply Level IV to Maintenance Level III for the Current System
WD35=C03+C1+C4+C5	Constant Payoff for Supply Level V to Maintenance Level III for the Current System
WD44=C04+C4	Constant Payoff for Supply Level IV to Maintenance Level IV for the Current System
WD45=C04+C4+C5	Constant Payoff for Supply Level V to Maintenance Level IV for the Current System
WDA11=C01+C1	Constant Payoff for Supply Level I to Maintenance Level I for the Alternative System
WDA12=C01+C1+C2	Constant Payoff for Supply Level II to Maintenance Level I for the Alternative System
WDA13=C01+C1+C3	Constant Payoff for Supply Level III to Maintenance Level I for the Alternative System
WDA14=C01+C1+C4	Constant Payoff for Supply Level IV to Maintenance Level I for the Alternative System
WDA15=C01+C1+C5	Constant Payoff for Supply Level V to Maintenance Level I for the Alternative System
WDA22=C02+C1	Constant Payoff for Supply Level II to Maintenance Level II for the Alternative System
WDA23=C02+C1+C3	Constant Payoff for Supply Level III to Maintenance Level II for the Alternative System

WDA24=C02+C1+C4	Constant Payoff for Supply Level IV to Maintenance Level II for the Alternative System
WDA25=C02+C1+C5	Constant Payoff for Supply Level V to Maintenance Level II for the Alternative System
WDA33=C03+C1	Constant Payoff for Supply Level III to Maintenance Level III for the Alternative System
WDA34=C03+C1+C4	Constant Payoff for Supply Level IV to Maintenance Level III for the Alternative System
WDA35=C03+C1+C5	Constant Payoff for Supply Level V to Maintenance Level III for the Alternative System
WDA44=C04+C4	Constant Payoff for Supply Level IV to Maintenance Level IV for the Alternative System
WDA45=C04+C4+C5	Constant Payoff for Supply Level V to Maintenance Level IV for the Alternative System

C. SENSITIVITY ANALYSIS

Sensitivity analysis is the analysis of the sensitivity of the result to a change in the variables that generated the result of the decision tree. Generally, an analysis is made of the point where a change in any one variable would cause a change in the final result. However, in this study it was found that there was no point where the current supply system would be selected over the alternative system for any change of the variables that make up the decision. The point where a variable would change is labeled the crossover point, and in this model there are no crossover points that would lead to the selection of the current supply system over the alternative supply system. Even though there is no crossover point, the analyst can still gain some information from the distance between the lines which represent the variables in each supply system (See Figure 10).

Figure 8 and Figure 9 are what the Data Program calls tornado diagrams. These diagrams show a sensitivity analysis of the variables of each supply system. The current system is depicted in Figure 8. The expected value for downtime for Equipment Type I of the current system is 41 days. In Figure 9, the expected value for downtime for Equipment Type I is 23 days in the alternative system. The range in the diagrams is not the plotted range for the variable, but is used by the program as a reasonable range for the variables expected values and the diagram is arranged so that the expected downtime is displayed. For example, variables C2 and C5 in fact range from 0 to a maximum value of approximately 55 days.

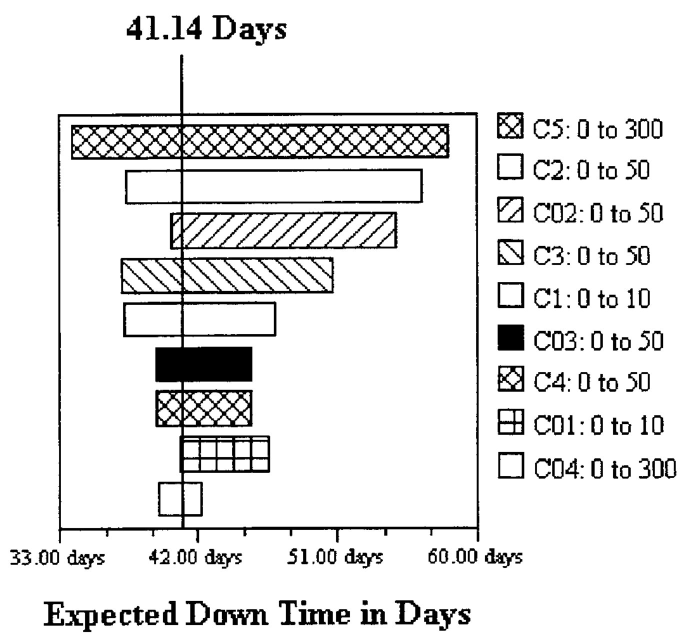

Figure 8. Current System Tornado Diagrams

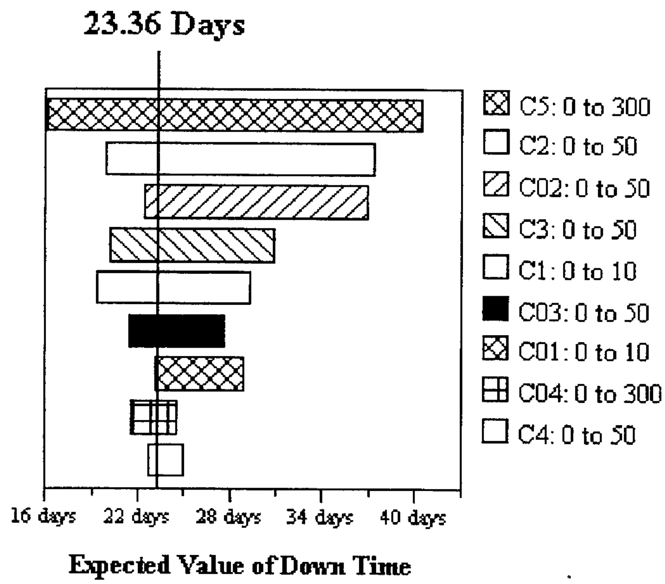

Figure 9. Alternative System Tornado Diagrams

Figure 10 shows a detailed analysis of variable C01 which is the repair time at Maintenance Level I. Variable C01 was chosen is because any change in the value of C01 will result in a change in the expected value of downtime. However, C01 affects both sub-trees for the current system and the alternative system equally, and any change in the variable C01 is reflected in slopes of lines for both systems.

Figure 11 shows a sensitivity analysis of the variable LA1. In this diagram, the lines for the current and alternative system diverge for the the reasonable range of LA1 of 0 to 1. Again, a change in a variable for both the current system and the alternative system will not produce a change in selection from the alternative system to the current system or in terms of the diagrams, a crossing of the lines that represent each system. In this diagram, the axes represent the expected downtime and failure rate. The lines are curved and approach 30 days for the current system, and 15 days for the alternative system, because failure rate LA1 divided by itself and a constant.

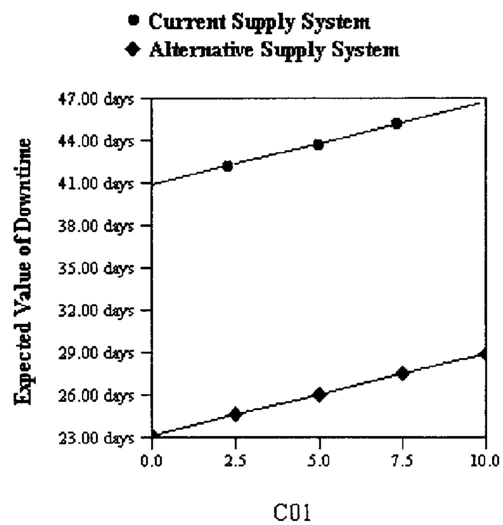

Figure 10. Sensitivity Analysis of Variable C01

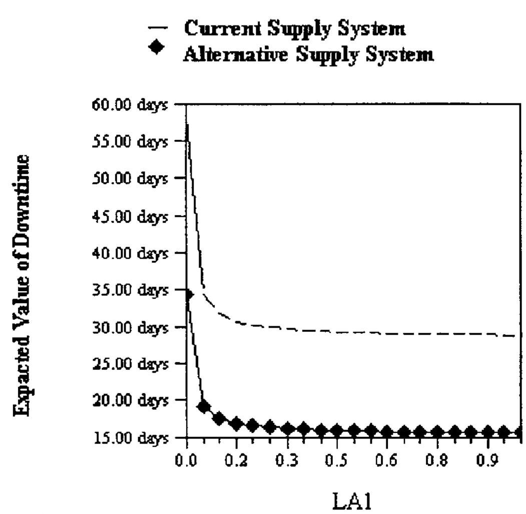

Figure 11. Sensitivity Analysis of Variable LA1

In summary, changes in the MTTF and equipment repair time do not affect the selection of the alternative system. This is an analysis of only two variables but is representative of the variables used in the model, where in no instance did any variable cause a switch the result of the decision tree from the alternative system to the current system.

D. RESULTS OF AVAILABILITY ANALYSIS

The results of the sensitivity analysis indicate that no single variable will select the current system over the proposed alternative system. The analysis also indicates that the expected availability of the equipment and the constant repair time used in the model did not affect a decision to select the alternative system. The selection of the systems by the Data Decision Support Program is based on the topography of each system. The alternative system has the shortest distance as measured by time to support the three types of equipment used by the Army battalion.

Table 10 is a summary of the results of the availability for the Army battalion. The availability clearly increases for the unit and therefore in terms of equipment availability, the Army units' readiness is increased under the alternative supply system. In Table 10 the Difference is Alternative system minus the current system operational readiness is shown. Percentage Increase is based on the current system. The average are simple arithmetic averages.

Table 10. Results of Study

Calculated Results for MOE, Operational Readiness of E_i

Equipment Type	Current System %	Alternative System %	Difference %	Percentage Increase Over Current System
E_1	46	60	14	30
E_2	40	53	13	33
E_3	32	44	12	38
Average			13	34

E. SUMMARY

This chapter has presented the results of the decision tree that was populated with the probability data developed in Chapter III. A sensitivity analysis indicated that no variable modeled in the decision tree would lead to the selection of the current supply system to minimize the MTTF for the equipment used by the battalion. Table 8 is a summary of the study and shows an increase in readiness for the Army unit. Chapter V presents the author's conclusions and recommendations for further research in a Point of Sale type of supply system to support the ROCs Armed Forces.

V. CONCLUSIONS AND RECOMMENDATIONS

In Chapter II an overview of the current supply system and a Point of Sale type of alternative to that system was presented. Chapter III developed a model using the GAMS Program of the probabilities of a part being available for the repair of one of three types of equipment used by an example ROC Army battalion. These probabilities were used in Chapter IV to populate a decision trees models using the Data Decision Support Program. The results of this models indicate a improvement in the readiness for the Army battalion by using the alternative supply system. Although the results generate an impressive increase in readiness for the unit, it must be remembered that the study is limited to the effects of the supply system on the availability of equipment for the unit.

This model did not include important factors to do with the limits of labor availability, stock level, minimum reorder points and the minimum purchase levels for parts. It was assumed in this model that those factors would be the same for either supply system. A simulation using one of the available software systems may yield data related to these factors.

A. CONCLUSIONS

Table 10 in Chapter IV, indicates an improvement in readiness for the Army battalion of greater than 30 percent. This would be an impressive figure in the real world. Although in reality the percentage of improvement may not be that large, this study suggests that the alternative Point of Sale type of supply system would lead to an improvement in the readiness of Army units. The result is achieved because the model for the alternative system has many less links than the current supply system model. In the real world, each length is a process which takes time and the time would vary with work schedule, workload, and the experience of the personnel at those levels.

In the sensitivity analysis in Chapter IV, no variance of a single variable will lead to a situation where the current system is better than the alternative supply system. In the analysis a change in the variable would only increase or decrease the magnitude of the

difference between the systems, but did not lead to any case where the current system produced higher readiness than the alternative system.

Although the resulting figures for unit readiness in the decision tree model are quite low, any change to the probabilities generated by the GAMS Program in Chapter III under those constraints will lead to an even lower readiness figure for the Army battalion. The failure rates used in the GAMS model for the original three types of equipment are based on the author's experience, but the model has led the author to believe that the true failure rates are much lower for these three types of equipment. However, this does not affect the validity of the model but would only lead to a situation where the increase in readiness for the alternative system was lower.

The ROC Armed Forces do not require a supply system designed to support global obligations and the far distant deployment of forces in peacetime. A Point of Sale system would provide for the ROCs needs and conserve resources of material and people in an environment of smaller defense budgets for more critical requirements.

The Point of Sale system requires an information system at each point where supplies are used. The nature of such as system would generate very good data on supply usage in the Armed Forces. This data would lead ultimately to better support and higher availability of the equipment used by the ROC Armed Forces.

This information system would allow for centralized control and analysis of usage data and provide a basis for the positioning of parts and equipment where they are most useful to the unit. This positioning would reduce transportation costs and the distribution time for parts and equipment and also lead to an increase in the readiness of the unit. This is a definite contrast with the current supply system which, in some cases, expends resources restocking warehouses to meet required inventory levels while overlooking lower level units that require parts to maintain their readiness.

An information system would also allow for detailed analysis of equipment issued to the units, and allow higher commands to make better decisions related to the equipment's meantimes between failure and the effect on a unit's readiness. Higher commands could make

and enforce decisions to increase the readiness for the equipment and have a database to use for decisions when obsolete equipment is to be replaced. General policies about overhauls and refurbishment of equipment would be centralized with the higher command which also has control of the budgetary functions of this operation. In this way, the higher command could delay or advance this process and make trade-offs to do with budget versus readiness rather than the typical trade-off made at the unit level, which is workload versus readiness.

B. RECOMMENDATIONS

There are four recommendations which result from this study:

- That the ROC Armed Forces develop a detailed simulation of a Point of Sale system and the current supply system using real supply data and equipment maintenance data. That this simulation include both the alternative of using commercial transportation to distribute and the reconfiguration of the existing government distribution system.

- The simulation should use real data because the distribution of repair times for real equipment is not only a function the reliability of the equipment, but the training level of the maintenance crew and the many tasks which military personnel are assigned. Supply data is primarily a civilian function and it varies with work week, the experience of the personnel and the legislative budget requirements.

- This study only addressed the readiness of the Army unit. It is recommended that a study address both cost and readiness differences between the two systems.

- This study could be improved by the use of a more realistic array of equipment supported with a better forecast of supply probabilities to support the equipment. To make this study more credible it should include a larger number of units and the units should be more representative of the ROC Armed Forces. The reason for this is that the supply system supports readiness for the entire ROC Armed Forces not just an Army unit. This improved study should take into account the supply priority system and produce results which would indicate the relative readiness of the array of ROC units.

This study is not in sufficient detail to support a recommendation that the ROC adopt a Point of Sale supply system for its Armed Forces. However, the results are encouraging,

in that, even without the consideration of cost, the analysis indicates that there would be a slight improvement in the readiness of the example Army battalion.

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